Atomic Layer Deposition (ALD) Coating for Permeation Half-Life Control of Ablator Capsules

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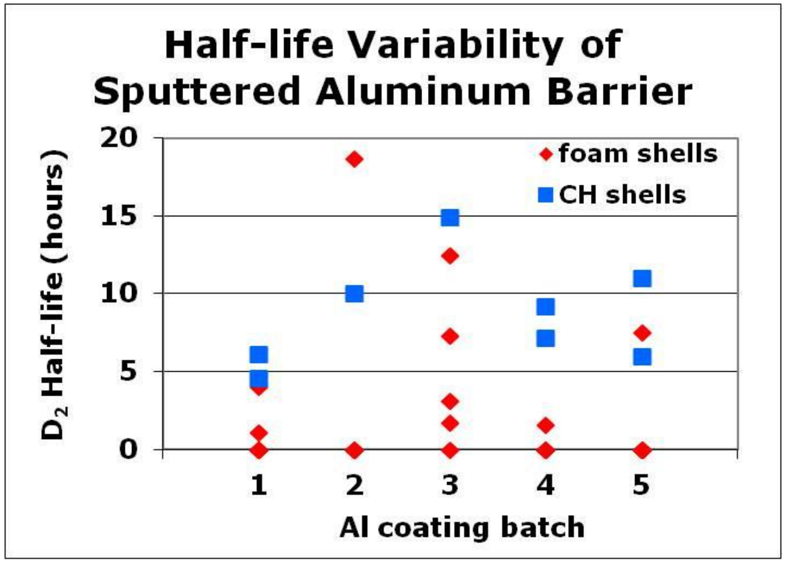
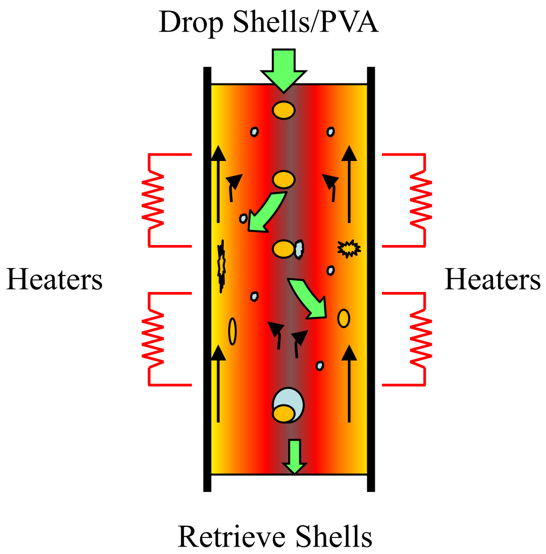
Atomic Layer Deposition (ALD) shows promise as permeation barrier alternative

- **Need to add permeation barrier to target shells to confine fusion fuel from fill until shot**
  - GDP target shells leak too fast, ~5 minute D_2 half-life
- **Desire ~4-10 hour D_2 half-life**
  - Long enough to retain fuel until shell is shot, but short enough to fill by permeation
- **Aluminum and PVA have previously been used as permeation barriers**
  - Sputtered Al – large variation in measured half-life
  - PVA Drop Tower – only 5% yield, <900µm OD shells
- **Initial ALD results**
  - High yield, high throughput, more repeatable
  - Successfully demonstrated with all size shells, various materials, manufactured defects, 3-D features

Previous methods use aluminum and PVA as permeation barriers, but are far from ideal

- **Sputter aluminum on shells mounted on post or sitting on Gelpak**
  - Little control over H-L, due to pinholes/voids in metal coating
  - Unreliable with very large spread even within same batch
  - Opaque layer limits characterization of interior
- **Drop shells covered in liquid PVA down tower with heated walls to solidify layer**
  - Low yield ~5%
  - Thick and non-uniform (3±1 μm)
  - Small shells only (OD <900μm)





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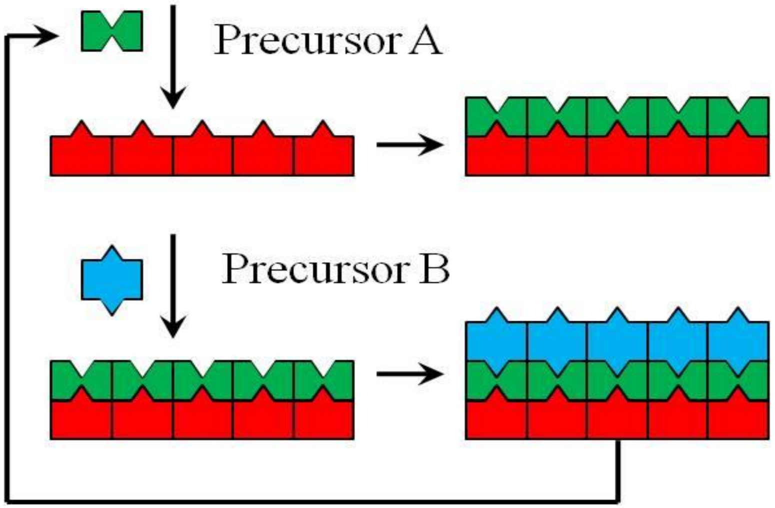
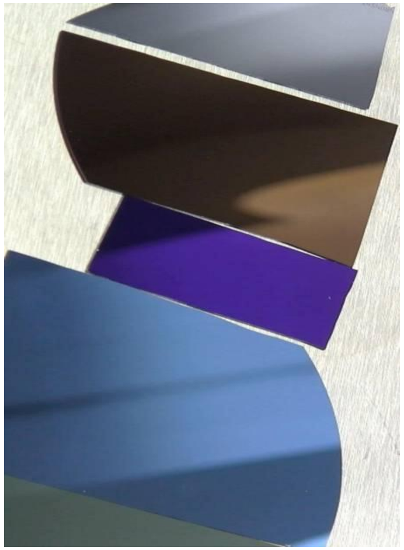
New Method: Atomic Layer Deposition (ALD) provides uniform, pinhole-free very thin coatings



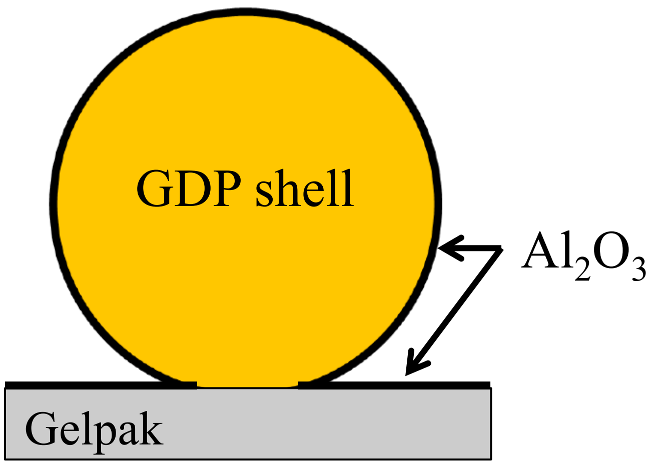
Uniform Al_2O_3 Coated on Si Wafer



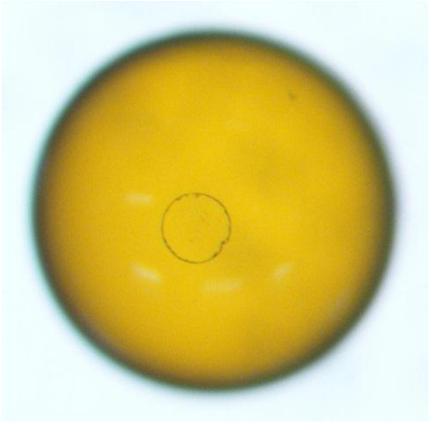
- **Grow one monolayer per cycle, ~0.1 nm**
  - Designed for thin films, typically <100 nm
  - Precursor gas bonds to surface only
  - Conforms to structures, high aspect ratios
- **Transparent Al_2O_3 process very robust**
  - Low coating temperature is ideal for plastics
  - Process does not damage shell

Shells are placed on Gelpak© in ALD chamber, leaving the contact spot uncoated

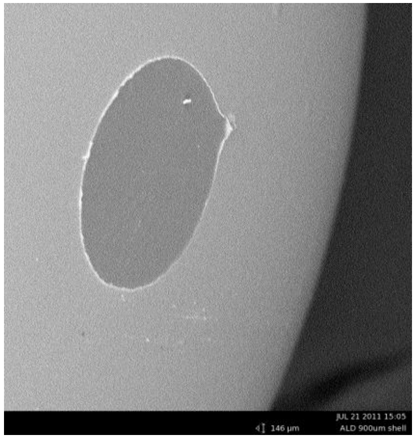
- **Conformal coating everywhere except where shell is in contact with Gelpak**
  - Contact spot area determined by Gelpak retention level (0,4,8), shell size, and shell weight
- **Using Gelpak 8 leaves potentially undesirable Gelpak still attached to shell in visible residue ring**



Optical



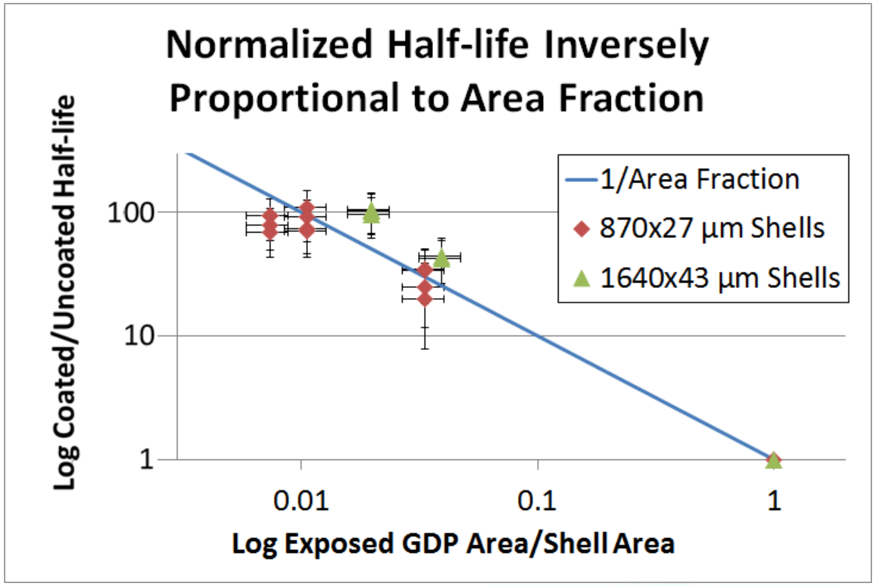
SEM

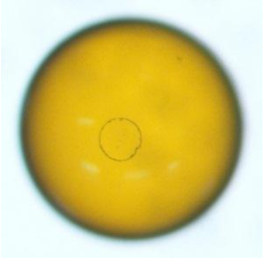


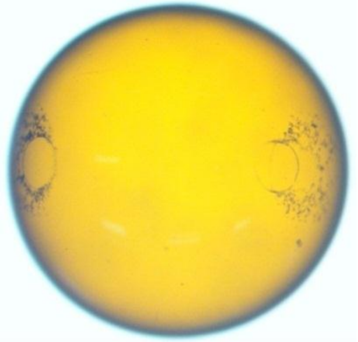
875 µm OD GDP Shell

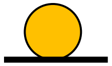
Method 1: Deliberately use area of exposed GDP at contact spot to scale permeation from uncoated shell

- **Permeation rate of D_2 through the Al_2O_3 layer << GDP shell wall**
  - Thickness of Al_2O_3 ~35 nm
- **Assume all gas permeates through exposed GDP at contact spot, then expect Half-life (inverse of permeation rate) to scale with inverse of exposed GDP area**
  - Area defined by residue ring
- **Higher order corrections to model**
  - Exposed GDP area different from residue ring
  - Al_2O_3 layer semi-permeable

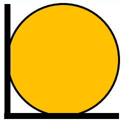








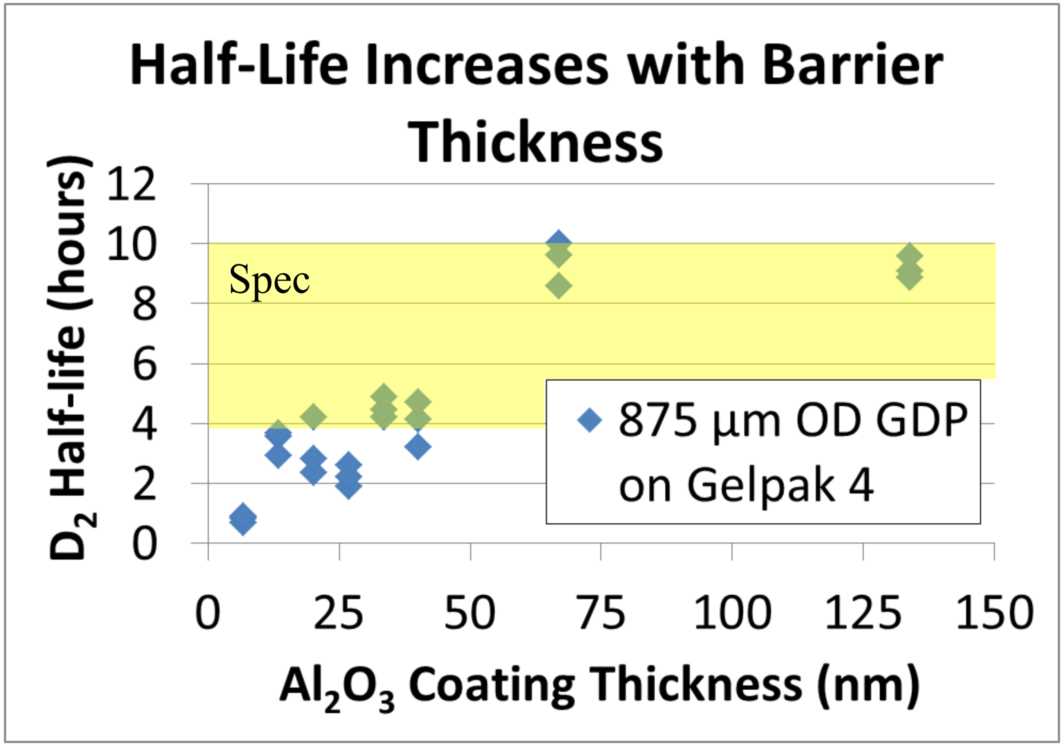
Gelpak 8
D 160 μm
875 μm OD



2xGelpak 8
D 230 μm
1640 μm OD

Method 2: Using a fixed contact area, vary the thickness to change the permeation rate

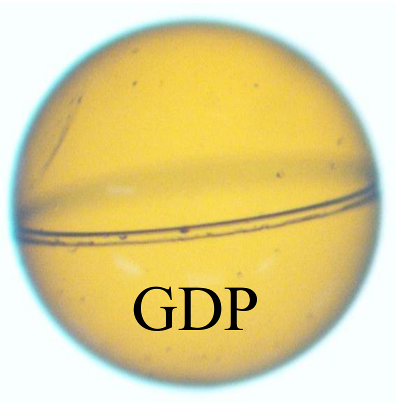
- **Large range of thicknesses produce desired barrier**
- **More repeatable and fine control compared to sputtered Al**
- **10 hour half-life max due to permeation through contact spot**
  - Up to 50 hour half-lives achieved by flipping shell during coating, sealing contact spots

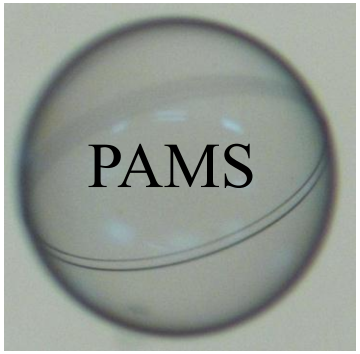


By varying exposed GDP area and Al_2O_3 thickness, we can achieve greater flexibility and control over barrier

Conformal ALD coatings are ideal for use on complex geometries and 3-D features

- **Transparent ALD coating conforms to surface, preserving features**
- **Example: successfully coated 8 µm deep x 30 µm wide trench**
  - 25 nm flipped coating (2x12.5 nm) resulted in 32 hr half-life w/ trench, 40 hr w/o
  - Sputtered permeation barrier was unsuccessful due to shadowing and other non-uniformities
- **Can be extended to other 3-D features and targets (not just shells)**
  - Up to 5000:1 aspect ratios in literature





875 µm OD
17 µm wall

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ALD coatings have other attractive benefits

- **Able to coat on variety of materials**
  – Plastic, silicon, oxides, metals, carbon
- **Thin ALD coatings are amorphous, stronger and harder compared to bulk materials**
- **Al_2O_3 process is temperature independent**
  – Demonstrated 120 °C, 80 °C, literature down to room temp
  – Ideal for temp sensitive plastics
- **Other materials available**
  – Oxides (including conductive), nitrides, metals
  – Adaptable to include other materials

Future research aims to dial in desired half-life and for shells to be used in real shot experiment

- **Acquire more data and statistics to further validate permeation barrier model**
- **Experiment with other ways of selecting exposed area/masking**
- **Investigate and eliminate residual ring when shell removed from Gelpak**
- **Study initial seeding behavior of Al_2O_3 using Quartz Crystal Microbalance (QCM) to further increase repeatability and understanding**